

**DECLINING TEMPORAL EFFECTIVENESS OF CARBON  
SEQUESTRATION: IMPLICATIONS FOR COMPLIANCE  
WITH THE UNITED NATIONAL FRAMEWORK CONVENTION  
ON CLIMATE CHANGE**

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**Abstract.** Carbon sequestration is increasingly being promoted as a potential response to the risks of unrestrained emissions of CO<sub>2</sub>, either in place of or as a complement to reductions in the use of fossil fuels. However, the potential role of carbon sequestration as an (at-least partial) substitute for reductions in fossil fuel use can be properly evaluated only in the context of a long-term acceptable limit (or range of limits) to the increase in atmospheric CO<sub>2</sub> concentration, taking into account the response of the entire carbon cycle to artificial sequestration. Under highly stringent emission-reduction scenarios for non-CO<sub>2</sub> greenhouse gases, 450 ppmv CO<sub>2</sub> is the equivalent, in terms of radiative forcing of climate, to a doubling of the pre-industrial concentration of CO<sub>2</sub>. It is argued in this paper that compliance with the United Nations Framework Convention on Climate Change (henceforth, the UNFCCC) implies that atmospheric CO<sub>2</sub> concentration should be limited, or quickly returned to, a concentration somewhere below 450 ppmv. A quasi-one-dimensional coupled climate-carbon cycle model is used to assess the response of the carbon cycle to idealized carbon sequestration scenarios. The impact on atmospheric CO<sub>2</sub> concentration of sequestering a given amount of CO<sub>2</sub> that would otherwise be emitted to the atmosphere, either in deep geological formations or in the deep ocean, rapidly decreases over time. This occurs as a result of a reduction in the rate of absorption of atmospheric CO<sub>2</sub> by the natural carbon sinks (the terrestrial biosphere and oceans) in response to the slower buildup of atmospheric CO<sub>2</sub> resulting from carbon sequestration. For 100 years of continuous carbon sequestration, the sequestration fraction (defined as the reduction in atmospheric CO<sub>2</sub> divided by the cumulative sequestration) decreases to 14% 1000 years after the beginning of sequestration in geological formations with no leakage, and to 6% 1000 years after the beginning of sequestration in the deep oceans. The difference (8% of cumulative sequestration) is due to an efflux from the ocean to the atmosphere of some of the carbon injected into the deep ocean. The coupled climate-carbon cycle model is also used to assess the amount of sequestration needed to limit or return the atmospheric CO<sub>2</sub> concentration to 350–400 ppmv after phasing out all use of fossil fuels by no later than 2100. Under such circumstances, sequestration of 1–2 Gt C/yr by the latter part of this century could limit the peak CO<sub>2</sub> concentration to 420–460 ppmv, depending on how rapidly use of fossil fuels is terminated and the strength of positive climate-carbon cycle feedbacks. To draw down the atmospheric CO<sub>2</sub> concentration requires creating negative emissions through sequestration of CO<sub>2</sub> released as a byproduct of the production of gaseous fuels from biomass primary energy. Even if fossil fuel emissions fall to zero by 2100, it will be difficult to create a large enough negative emission using biomass energy to return atmospheric CO<sub>2</sub> to 350 ppmv within 100 years of its peak. However, building up soil carbon could help in returning CO<sub>2</sub> to 350 ppmv within 100 years of its peak. In any case, a 100-year period of climate corresponding to the equivalent of a doubled-CO<sub>2</sub> concentration would occur before temperatures decreased. Nevertheless, returning the atmospheric CO<sub>2</sub> concentration to 350 ppmv would reduce longterm sea level rise due to thermal expansion and



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might be sufficient to prevent the irreversible total melting of the Greenland ice sheet, collapse of the West Antarctic ice sheet, and abrupt changes in ocean circulation that might otherwise occur given a prolonged doubled-CO<sub>2</sub> climate. Recovery of coral reef ecosystems, if not already driven to extinction, could begin.

## 1. Introduction

The atmospheric carbon dioxide concentration is increasing as a result of anthropogenic emissions in excess of the rate of absorption by natural carbon sinks (the terrestrial biosphere and oceans). Capturing a portion of the CO<sub>2</sub> released from the combustion of fossil fuels or biomass and permanently burying or sequestering this carbon could contribute to balancing emissions and sinks and thereby stabilize the atmospheric CO<sub>2</sub> concentration. Carbon sequestration involves, first, separating CO<sub>2</sub> from the other products of the combustion of fossil fuels or biomass; second, compressing and transporting CO<sub>2</sub> to sequestration sites; and third, injecting CO<sub>2</sub> into the disposal sites. The costs and technologies involved in all of these steps, and the global storage potential of different kinds of potential storage sites, are discussed in detail in Riemer et al. (1999). An overview of concepts, research programmes, and the current state-of-the-art can be found in IEA (2001a–c), Herzog (2001), and Halloway (2001).

The collection of CO<sub>2</sub> released from the combustion of fossil fuels or biomass is practical only at large, centralized facilities such as electrical power plants, district-heating plants, and possibly at large industrial sites. This limits the fraction of energy-related CO<sub>2</sub> emissions that could be captured to perhaps one third. Projections of the energy penalty associated with the post-combustion capture of CO<sub>2</sub> from electrical power plants by David and Herzog (2000) indicate an increase in fuel use of about 10% for either integrated gasification-combined cycle coal power plants or natural gas combined cycle power plants, with just under 90% of the product CO<sub>2</sub> captured. IEA (2001c) also foresees about a 10% energy penalty using natural gas, but no less than a 17% energy penalty using coal.

If hydrogen were to be produced from fossil fuels during the transition to a renewable-energy-based hydrogen economy, and used in the transportation sector or for heating, then a much larger fraction of the CO<sub>2</sub> emission associated with the use of fossil fuels could be subject to partial capture, and with a smaller energy penalty than for the post-combustion capture of CO<sub>2</sub>. The production of hydrogen by gasification of coal or biomass or steam reforming of natural gas in pure oxygen yields two streams of CO<sub>2</sub>, one diluted in stack gases, and the other in a highly concentrated stream that is separated from the H<sub>2</sub> using a pressure swing absorption unit. The latter (about 70% of the total for steam reforming) can be captured at low cost and with no energy penalty (it needs to be separated from the H<sub>2</sub> in any case). Energy would be required for the subsequent compression of CO<sub>2</sub> and transport to disposal sites. Williams (1998) has analyzed the costs and

energy use associated with partial capture of CO<sub>2</sub> associated with the production of hydrogen from natural gas, coal, and biomass, and its subsequent compression to 110 atmospheres pressure and injection into a partially depleted gas field, or transport and injection into an aquifer 250 km from the hydrogen production plant. The fraction of CO<sub>2</sub> captured at the hydrogen plant ranges from 71% using natural gas to 97% using biomass, with an energy penalty of 2.3% using natural gas, 5.0% using coal, and 5.3% using biomass when all upstream and downstream emissions are accounted for. Sequestration in the oceans would entail a greater penalty, due to the greater transport distance that would normally be involved, but the energy required to liquefy the CO<sub>2</sub> prior to its injection into the ocean would be comparable to that needed for compression to 110 atmospheres pressure.\*

Potential carbon sequestration sites are depleted oil and gas fields, existing oil and gas fields with CO<sub>2</sub> injected in order to increase the fraction of oil and gas that can be extracted from the fields, deep aquifers, coal beds, and the deep ocean (which is where most of the anthropogenic CO<sub>2</sub> will eventually end up). In the case of deep coal beds, CO<sub>2</sub> molecules would displace methane (CH<sub>4</sub>) adsorbed to the surface of coal particles. Given the relative affinities of coal for CH<sub>4</sub> and CO<sub>2</sub>, it is possible that more carbon could be sequestered as CO<sub>2</sub> than released as CH<sub>4</sub> (Byrer and Guthrie, 1999). The methane would be captured and used as an energy source, but the coal would be rendered unminable in the process (at least, not without releasing the sequestered CO<sub>2</sub>).

Table I summarizes various estimates of the amount of CO<sub>2</sub> that could be stored in various land-based (or subsurface marine) storage sites. The largest uncertainty concerns the extent to which CO<sub>2</sub> could be permanently stored in deep aquifers, without eventual leakage to the atmosphere. This in turn depends on the extent to which small-scale structural traps combined with dissolution of CO<sub>2</sub> into pore fluids is sufficient to permanently immobilize the injected CO<sub>2</sub> without the existence of large-scale structural traps. As indicated in Table I, the minimum estimated sequestration potential, excluding dissolution in ocean water, is about 300 Gt C (around 50 years of current fossil fuel emissions).

The oceans have the ability to permanently store several thousand Gt C. Carbon dioxide that is sequestered in the ocean would be liquefied first and injected at a depth of 3000 m or so, either from seabed pipes or from pipes suspended from moving ships. These options pose significant technical challenges, but these are not

\* Williams (1998) indicates an energy requirement for compression from 1.3 to 110 atmospheres pressure of about 400 kWh/tC (1.44 GJ/tC). Haugen and Eide (1996) indicate that 55–60 MW of power would be needed to liquefy the CO<sub>2</sub> produced by a 500 MW coal-fired power plant. Given a power plant efficiency of 33% and a coal emission factor of 24 kg C/GJ, this implies an energy requirement of 1.5–1.7 GJ/tC. Also note that, although this is a 10–12% energy penalty for the liquefaction of CO<sub>2</sub> from a coal power plant, it is less than a 2% penalty for the liquefaction of 71% of the CO<sub>2</sub> released by steam reforming of natural gas. For a steam reforming efficiency of 89%, a natural gas emission factor of 13.5 kg C/GJ, and 71% capture, the amount of CO<sub>2</sub> that needs to be liquefied is 0.0107 tC/GJ H<sub>2</sub>, and the energy requirement is 1.6–1.8% the energy content of the product H<sub>2</sub>.

Table I

Estimates of the global carbon sequestration potential, excluding deep ocean disposal. Based on summaries presented in Parson and Keith (1998) and Williams et al. (2000)

Reservoir	Storage Potential (Gt C)
Aquifers, if structural traps are needed	50
Aquifers, if structural traps are not needed	2700–13000
Enhanced oil recovery	20
Depleted oil fields	40–100
Depleted gas fields	90–400
Deep coal beds	100–300
Minimum total	about 300

believed to be insurmountable (Nihous, 1997). However, the fraction of injected carbon that would remain in the ocean in steady state is only about 85% (prior to the partial dissolution of carbonate sediments), so injection of 2000 Gt C (for example) would still produce an atmospheric CO<sub>2</sub> increase of about 300 Gt C (corresponding to a concentration increase of about 150 ppmv). This would be sufficient, in combination with the CO<sub>2</sub> (past and future) that is not sequestered, to push the atmospheric CO<sub>2</sub> concentration close to a doubling of the pre-industrial concentration (or beyond), something that runs the risk of significant disruption of climate, ecosystems, and food-producing systems in at least some parts of the world. Furthermore, injection of such large amounts of CO<sub>2</sub> in the ocean would likely have profound effects on marine life by decreasing the pH of seawater and significantly reducing the extent of supersaturation of surface water with respect to calcium carbonate (Harvey, 2003). Partial dissolution of carbonate sediments would neutralize the decrease in pH and allow the oceans to store another 3–4% of the originally injected CO<sub>2</sub>, but only after a lag of 2000 years (Kheshgi and Archer, 1999). Thus, reliance on carbon sequestration in the oceans as the primary means of limiting the climatic effects of fossil fuel CO<sub>2</sub> is not an acceptable solution. However, sequestration of a few hundred Gt C in the oceans could usefully be part of a broader strategy to limit the buildup of atmospheric CO<sub>2</sub>.

The rationale for and organization of this paper are as follows: carbon sequestration is being promoted by the fossil fuel industry and by some political leaders and analysts as an at-least partial solution to the global warming problem (e.g., Parson and Keith, 1998; Herzog 2001). However, as indicated above and discussed in more detail elsewhere (Harvey, 2003), reliance on sequestration of carbon in the deep oceans to any significant extent, in place of equivalent reductions in fossil fuel use, leads to substantial increases in atmospheric CO<sub>2</sub> concentration and changes in ocean chemistry over a period of several hundred years. Furthermore, as noted

above, the sequestration potential in terrestrial aquifers and oil or gas fields could be limited to 300 Gt C, at least not without substantial long-term leakage. Therefore, the potential role of carbon sequestration as an at-least partial substitute for reductions in fossil fuel use can be properly evaluated only in the context of a long-term acceptable limit (or range of limits) to the increase in atmospheric CO<sub>2</sub> concentration. Fortunately, the key principles needed to determine what this limit or range of limits should be, and the implicit value judgements in determining such as limit, are already enshrined in the United Nations Framework Convention on Climate Change (henceforth, the UNFCCC). The UNFCCC is a legally-binding document signed and ratified by 182 of the world's countries. It provides a sound and agreed starting point for assessing the usefulness of carbon sequestration.

This paper therefore begins with arguments concerning an acceptable range of allowable CO<sub>2</sub> concentrations. Having established a range of allowable CO<sub>2</sub> concentrations that is consistent with the UNFCCC and current scientific understanding, a set of representative emission scenarios is derived in a simple and transparent manner, so as to serve as a series of reference cases against which varying degrees of carbon sequestration can be applied. The goal is to assess under which circumstances (baseline emission scenarios) carbon sequestration can bring and maintain atmospheric CO<sub>2</sub> concentration at or below the previously determined limit. For those baseline emission scenarios for which carbon sequestration could move the world from non-compliance to compliance with CO<sub>2</sub> concentration limits that are consistent with the UNFCCC, the amount, timing, and nature (i.e., terrestrial versus marine) of carbon sequestration that would be needed is determined through use of a simple but well-validated coupled climate-carbon cycle model. The impact of carbon sequestration on atmospheric CO<sub>2</sub> concentration depends on the carbon cycle response to carbon sequestration, the dynamics of which are clarified here by showing and explaining the response to an impulse sequestration and to idealized, uniform rates of sequestration.

## **2. Determining an Acceptable Range of CO<sub>2</sub> Concentrations**

Our understanding of the science of global warming has progressed to the point where the major uncertainty now is where, within the 350–450 ppmv range, the atmospheric CO<sub>2</sub> concentration should be capped so as to avoid ‘dangerous anthropogenic interference with the climate system’, the declared goal of the UNFCCC (UN, 1992). Although ‘dangerous’ is not defined by the UNFCCC, such climatic change as is allowed must be such as ‘to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner’. Since this document has been accepted and ratified by almost all nations in the world, a number of value judgements have already been implicitly accepted, and do not need further debate. For example, the value judgement has already been made that ecosystems

are worthy of protection (by ensuring that rates and magnitudes of climatic change and such as to allow their natural adaptation), irrespective of their economic value to humans. The requirement that GHG concentration caps be such as to enable economic development might appear to place a lower limit on the allowable caps, and possibly conflict with the requirements concerning ecosystems and food production, except for the proviso that economic development be *sustainable*. This proviso over-rides the proclivity of economists to try to determine supposedly 'optimal' emission levels based on fanciful cost-benefit analysis with discount rates that ensure that the resulting system is anything but sustainable (for a stimulating discussion of the broader question of discounting, economic growth, and sustainability, see Daly (1996)).

The acceptable range of maximum CO<sub>2</sub> concentration depends on (i) the increases in concentrations of non-CO<sub>2</sub> GHGs that occur along the an increase in CO<sub>2</sub>, as these determine the total radiative forcing associated with a given CO<sub>2</sub> increase; (ii) the relationship between concentrations and time-dependent climatic change; and (iii) the relationship between climatic change and a range of key impacts. The first step depends in a straightforward manner on the scenarios for emissions of non-CO<sub>2</sub> GHGs, while a substantial amount has already been written concerning climate response and impacts, including up-to-date and exhaustive reviews for the Third Assessment Report of Intergovernmental Panel on Climate Change (IPCC). There is therefore no need to discuss these issues extensively here, but it is appropriate to summarize the key scientific evidence that leads to the conclusion that compliance with the UNFCCC implies a CO<sub>2</sub> concentration limit within the 350–450 ppmv range.

The single most important parameter in determining the climatic response to a given greenhouse gas (GHG) buildup is the *climate sensitivity*. Strictly speaking, the climate sensitivity is the ratio of the globally averaged, equilibrium temperature change to the globally averaged radiative forcing. It is common to refer to the globally averaged equilibrium warming for a doubling of atmospheric CO<sub>2</sub> concentration ( $\Delta T_{2x}$ ) as the climate sensitivity, and this convention will be adopted here. A CO<sub>2</sub> concentration of 450 ppmv roughly corresponds to a doubling of the pre-industrial atmospheric CO<sub>2</sub> concentration when the heating effect of other GHGs is taken into account, assuming *stringent* limitations in emissions of other GHGs.\* Under most business-as-usual scenarios, GHG concentrations rise far in excess of a CO<sub>2</sub>-doubling equivalent (see Prentice et al., 2001, Figure 3.12).

\* If a CO<sub>2</sub> doubling gives a radiative heating of 3.75 Wm<sup>-2</sup> (the central estimate), then a concentration of 450 ppmv gives a heating of 2.57 Wm<sup>-2</sup>, which means that additional heating of 1.18 Wm<sup>-2</sup> will give the equivalent of a CO<sub>2</sub> doubling. The current radiative heating by non-CO<sub>2</sub> GHGs is around 1.4 Wm<sup>-2</sup>. For the reductions in emissions or forcing by non-CO<sub>2</sub> GHGs in Scenario 5 (described later), the non-CO<sub>2</sub> radiative forcing is 1.2 W m<sup>-2</sup> in 2100. As these are rather stringent emission reductions, one can conclude that a CO<sub>2</sub> concentration of 450 ppmv will correspond to at least the equivalent of a doubling of the CO<sub>2</sub> concentration.

Table II

Assumptions concerning non-CO<sub>2</sub> GHGs and aerosols. SRES = Special Report on Emission Scenarios, prepared for the Intergovernmental Panel on Climate Change (Houghton et al., 2001)

Constituent	Scenarios 1–4	Scenario 5
CH <sub>4</sub> , fossil fuel related	Emission proportional to fossil fuel CO <sub>2</sub> emission	
CH <sub>4</sub> , biomass related	Emission increases by factor of 2.7 between 2000–2100	Emission decreases by 50%, 2000–2100
N <sub>2</sub> O	Emissions as in SRES A2p	Emission decreases by 50%, 2000–2100
non-HFC halocarbons	Emissions end between 2020–2050	
HFCs	Emissions as in SRES A2p	SRES A2p emission times a factor decreasing from 1.0–0.25 between 2000–2100
SF <sub>6</sub>	Emissions as in SRES A2p	Emission decreases by 50%, 2000–2100
Tropospheric ozone <sup>a</sup>		
CH <sub>4</sub> -related	Proportional to anthropogenic CH <sub>4</sub> emission	
Biomass burning-related	Proportional to biomass CO <sub>2</sub> emission	
Fossil fuel-related	Proportional to fossil fuel CO <sub>2</sub> emission times a factor that varies from 1.0–0.33 between 2000–2100	
S aerosol	Proportional to fossil fuel CO <sub>2</sub> emission times a factor that varies from 1.0–0.25 between 2000–2050	

<sup>a</sup> Forcing due to tropospheric O<sub>3</sub> is assumed to have been 0.35 W m<sup>-2</sup> in 1990 (the central estimate of Ramaswamy et al., 2001), of which 0.12 W m<sup>-2</sup> is assumed to be related to the use of fossil fuels, 0.15 W m<sup>-2</sup> is assumed to be related to biomass burning, and 0.08 W m<sup>-2</sup> is assumed to be related to the buildup of atmospheric CH<sub>4</sub>.

A wide variety of evidence (discussed in detail in Chapter 9 of Harvey (2000)) indicates that  $\Delta T_{2x}$  is likely to fall between 2–4 °C, although a much broader range (from 1 to 5 °C or more) cannot be ruled out (Andronova and Schlesinger, 2001; Forest et al., 2002; Harvey and Kaufmann, 2002; Knutti et al., 2002). This evidence includes three-dimensional atmospheric general circulation models, which attempt to simulate the major climate feedbacks that are responsible for determining the climate sensitivity. It includes direct observations of the processes in the atmosphere governing the most important single climate feedback, the increase in the amount of water vapor in the atmosphere that occurs as the atmosphere warms. It includes inferences based on the study of past climates, such as the warm conditions during

the Cretaceous period (144–66 million years ago) and during the peak of the last ice age (centered around 18000 years ago), and inferences based on the observed warming during the past 140 years. Although each of these approaches is subject to large uncertainties and difficulties, there is broad agreement between them and, collectively, they indicate that the climatic response to a benchmark CO<sub>2</sub> doubling is potentially of great concern.

The likely minimum possible warming for a CO<sub>2</sub> doubling-equivalent – 1 °C in the global average – is not particularly alarming, although even for this sensitivity, an eventual warming far in excess of 1 °C would occur for most business-as-usual GHG emission scenarios. Furthermore, an increase in atmospheric CO<sub>2</sub> concentration to 450 ppmv would have profound impacts on marine life, irrespective of the climate sensitivity, through changes in ocean chemistry. In particular, a 450 ppmv atmospheric concentration would be associated with a decrease in surface water pH by about 0.2 units and a decrease in the supersaturation of surface water with respect to CaCO<sub>3</sub> by about 25% according to calculations presented below. The latter is almost certain to adversely affect coral reef and marine calcareous microorganisms (at the base of the marine food web), although the magnitude of the impact is unclear. Calcification rates of coral reef and free-swimming planktonic organisms could remain relatively constant as CaCO<sub>3</sub> supersaturation decreases, then drop precipitously when some threshold is crossed (Kleypas et al., 1999). Thus, the case can be made to limit the atmospheric CO<sub>2</sub> concentration to no more than 450 ppmv even if the climate sensitivity is as small as 1 °C, and possibly to less than 450 ppmv.

However, there is a substantial risk that the climate sensitivity for a CO<sub>2</sub> doubling is substantially in excess 1 °C. If  $\Delta T_{2x} = 5\text{ °C}$ , then we run a high risk of catastrophic climatic change even if GHG concentrations are limited to a CO<sub>2</sub> doubling-equivalent. There is a continuously increasing risk of serious impacts as the projected warming increases from 1 to 5 °C. A 1 °C warming (i.e., close to that already experienced) to a 2 °C warming (optimistic case) risks killing most or all of the coral reefs in the world, particularly in combination with the afore-mentioned decrease of CaCO<sub>3</sub> supersaturation and other stresses (Kleypas, 1998; Hoegh-Guldberg, 1999; Wilkinson, 1999; Wellington et al., 2001; Dennis, 2002). Coral reefs represent an ecosystem that is enormously important from a biological, economic, and human well-being point of view (as summarized by Hoegh-Guldberg, 1999). Estimates of the number of people at risk from water shortages, hunger, malaria, and flooding by Parry et al. (2001), as a function of global average warming, show an abrupt increase between 1 and 2 °C global mean warming. Assessments of the impact of a doubled-CO<sub>2</sub> climate (which spans a range of temperature and precipitation changes) frequently show decreases in agricultural yields in specific regions of 10–20% and more, even after allowing for the beneficial physiological effects of higher CO<sub>2</sub> and for adaptation (see Gitay et al., 2001, Table 5.4). Most studies of agricultural impacts assume full realization of the beneficial physiological effects of higher CO<sub>2</sub>, as measured in experimental set-



tings, and furthermore, assume that an effective CO<sub>2</sub> concentration (from a climatic point of view) of 550 ppmv (for example) corresponds to a real concentration of 550 ppmv (i.e., Arnell et al., 2002; Aggarwal and Mall, 2002). There are substantial reasons for doubting whether the full beneficial effects will occur in practice, even if the correct CO<sub>2</sub> concentration is used (Wolfe and Erickson, 1993; Darwin and Kennedy, 2000).

A 4 °C warming risks provoking the complete and irreversible melting of the Greenland ice sheet and the collapse of the West Antarctic ice sheet, leading to a sea level rise of 10 m over a period of a few thousand years (Harvey, 2000, Chapter 12). A global mean warming of 3–4 °C over the course of the next century could have highly disruptive effects on many forest ecosystems (Arnell et al., 2002), although there is a large range of opinion among forest ecologists (Morgan et al., 2001). Of particular concern are simulations by the HadCM3 model at the Hadley Centre in the U.K., in which almost the entire Amazon rainforest is replaced by semi-desert by the 2080s due to a drastic reduction in rainfall in the Amazon basin in association with a global mean warming of about 3.3 °C (White et al., 1999). In the HadCM2 model (an earlier Hadley Centre model), the Amazon rainforest is still largely intact by 2100 (when the simulation ends) but with greatly reduced productivity, and a positive climate-carbon cycle feedback has caused a significant enhancement in the buildup of atmospheric CO<sub>2</sub> (Cox et al., 2000).

It follows from the above that, if  $\Delta T_{2x} = 1$  °C, then GHG concentration increases that are collectively equivalent to a CO<sub>2</sub> doubling might be permissible, although there are still important concerns about impacts through changes in marine chemistry and impacts on coral reefs. If, on the other hand,  $\Delta T_{2x}$  is close to 5 °C, then GHG concentrations must be kept substantially below a CO<sub>2</sub> doubling-equivalent. Since, at this point in time, we do not know what the true climate sensitivity is, and the repercussions of changes in marine chemistry are uncertain, a CO<sub>2</sub>-doubling equivalent (450 ppmv) must be regarded as dangerous. Note that it is not necessary to show that 450 ppmv CO<sub>2</sub> leads to *certain* impacts that violate the UNFCCC principles of protecting ecosystems and food security; it is simply necessary to show that such a concentration represents dangerous interference in the climate system, that is, that there are non-negligible risks to important ecosystems and to food security. This is clearly the case.

Since the goal of the UNFCCC is to *avoid* dangerous anthropogenic interference in the climate system, and since 450 ppmv CO<sub>2</sub> is dangerous (given current uncertainties, and heating effects from other gases), it follows that current policy should be directed at stabilization in the range of 350–400 ppmv (as advocated by Azar and Rodhe, 1997). Further research *might* show that a CO<sub>2</sub> concentration as high as 450 ppmv is acceptable (although this depends in part on human values), but is exceedingly unlikely to dispense with the need to limit the CO<sub>2</sub> concentration to at least 450 ppmv.

Since the current atmospheric CO<sub>2</sub> concentration (372 ppmv) already exceeds 350 ppmv, stabilization of atmospheric CO<sub>2</sub> at 350 ppmv would require creating

negative emissions by sequestering carbon produced from the gasification of biomass (grown sustainably) prior to its use as an energy source in place of fossil fuels. However, the magnitude of the negative emission that can be created is limited by the rate at which biomass primary energy can be supplied and the fraction of this from which CO<sub>2</sub> emissions can be captured and transported to sequestration sites.

### 3. Baseline Emission Scenarios

A set of scenarios for emissions of CO<sub>2</sub> from fossil fuels will now be presented for two reasons: (i) to serve as reference cases to which various carbon sequestration scenarios can be applied, and (ii) for those reference cases in which carbon sequestration could potentially lead to compliance with the UNFCCC, to illustrate the broader context in which carbon sequestration could make the difference between compliance and non-compliance. To achieve the latter objective, it is necessary to decompose past and future CO<sub>2</sub> emissions in a simple and transparent manner.

Past and future CO<sub>2</sub> emissions will be decomposed here as the product of the following factors:

- population ( $P$ ),
- economic output (dollars) per person ( $\$/P$ ),
- average primary energy consumption (joules) per dollar of economic output ( $J/\$$ ),
- average CO<sub>2</sub> emission per joule of primary energy consumption ( $E/J$ ).

Thus,

$$\text{Emission} = P \times (\$/P) \times (J/\$) \times (E/J). \quad (1)$$

The historical variation of each of these factors (up to 1990) is presented in Hoffert et al. (1998). The current values of these four factors or the quantities needed to compute them are as follows: population, 6.055 billion in 2000 (Lutz et al., 2001); gross world product, U.S.\$44.9 trillion in 2000 (Worldwatch Institute, 2002); primary energy use, 419.7 EJ in 1999 (IEA, 2001); fossil fuel CO<sub>2</sub> emission, 6.239 Gt C in 1999 (Marland et al., 2002).

With regard to population, we consider the 20th and 80th percentile curves among the population scenarios of Lutz et al. (2001), that is the population growth that exceeds the population growth in 20% and 80%, respectively, of the scenarios generated. In the first case, global population peaks at 7.8 billion near 2050, then declines to 6.4 billion by 2100. In the second case, global population peaks at 10.75 billion by 2085, then declines slightly. With regard to global average GDP per capita, we consider two scenarios, one with growth of 1.6% per year for the entire century (as in the IPCC IS92a scenario, described in Hoffert et al., 1998), and another with growth that decreases linearly from 1.6%/year in 2000 to 0.8% per year in 2100. The low-growth scenario should not be construed as representing

a poorer global society or a lower standard of living. In simple models of future CO<sub>2</sub> emissions (e.g., Edmonds and Reilly, 1983), the growth of GDP is given by the product of a growing labor force and increasing 'productivity' per person. However, individuals (especially those in currently developed countries) may increasingly decide to channel increased productivity into greater day-to-day leisure which, by many counts, would represent an improvement in the quality of life.

The third term in Equation (1) (primary energy use per unit of GDP) is referred to as the *energy intensity* of the economy. It depends not only on the efficiency with which energy is transformed and used, but also on the mix of goods and services produced by the global economy. The energy intensity of the global economy has been decreasing by about 1% per year since 1960 (Hoffert et al., 1998). Two scenarios are considered here: one in which an improvement of 1% per year continues until 2100, and the other in which an improvement of 2% per year occurs (beginning in 2005). These improvements lead to reductions in global average energy intensity by 2100 by factors of 2.7 and 7.0, respectively, compared to 2000. Even the latter is within the realm of technical feasibility, as can be seen if a systems approach to energy use is adopted (see Harvey (2005) for a comprehensive discussion of this issue).

The fourth term in Equation (1) (carbon emission per unit of primary energy) is referred to as the *carbon intensity* of the energy system. For future projections, it is easier to start with the present carbon-free primary power supply (2.7 TW) and to postulate various exponential growth rates; here, we consider growth rates of 0.5% per year and 2.0% per year (subject to the constraint that carbon-free power supply does not exceed total power demand). These two scenarios result in a carbon-free power supply in 2050 of 3.5 TW and 7.4 TW, respectively. The latter is likely to be extremely difficult if based entirely on renewable energy sources (solar, wind, biomass); nuclear energy and carbon sequestration may have a limited but important role to play (carbon-free power sources are critically discussed in Harvey (2005)). Any carbon sequestration required to add 0.8–4.7 TW of carbon-free power by 2050 would be in addition to the carbon sequestration discussed below that is required in order to stabilize atmospheric CO<sub>2</sub> at 350–400 ppmv.

Figure 1 shows the scenarios for population growth, per capita GDP, and global primary power demand adopted here. Also shown are the resulting fossil fuel CO<sub>2</sub> emissions for four combinations of the four factors given in Equation (1). In Scenario 1 (high population, high GDP growth, 1% per year energy intensity decline, and 0.5% per year growth of carbon-free power), CO<sub>2</sub> emissions grow from 6.5 Gt C/yr in 2000 to 27 Gt C/yr in 2100. In Scenario 2 (same as Scenario 1 except for 2%/yr decline in global energy intensity), CO<sub>2</sub> emissions peak at about 9 Gt C/yr around 2060, then decline to 7 Gt C/yr by 2100. In Scenario 3 (same as Scenario 2 except for 2%/yr growth of carbon-free energy), CO<sub>2</sub> emissions peak at 7.7 Gt C/yr in 2030, then decline to zero by 2100. Finally, in Scenario 4 (same as Scenario 3 except for low population and low economic growth), CO<sub>2</sub> emissions decline from 6.9 Gt C in 2005 to zero by 2075.

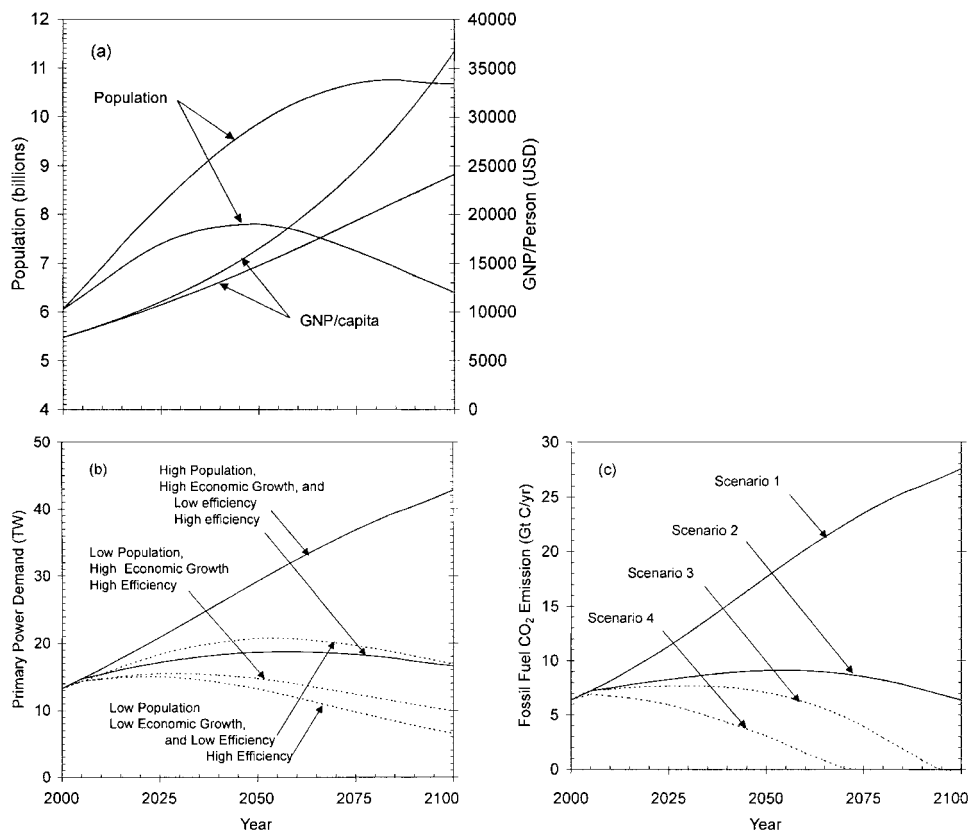


Figure 1. (a) Population and GNP/capita scenarios used here. (b) Primary power demand resulting from different combinations of the population, GNP/capita, and energy intensity scenarios. 'Low efficiency' and 'high efficiency' pertain to a 1%/yr and 2%/yr decreases in energy intensity, respectively, the latter beginning in 2005. (c) Fossil fuel CO<sub>2</sub> emissions for scenarios one to four, as described in the text.

#### 4. Baseline CO<sub>2</sub>-Concentration and Temperature Scenarios

To translate the emissions shown in Figure 1 into CO<sub>2</sub> concentrations and then into temperature change, the coupled climate-carbon model of Harvey and Huang (2001) and Harvey (2001) is used. This model includes what is essentially a one-dimensional upwelling diffusion model of the ocean, except that polar regions are resolved along with convective mixing. It has a 6-box, globally-aggregated model of the terrestrial biosphere. The oceanic part of the model has been extensively tested against observed steady state and transient variations in a number of separate tracers, and further validation-test results will be presented here. It is used to study the impact of a wide range of ocean sequestration scenarios in Harvey (2003).

The amount of carbon that needs to be sequestered for a given emission scenario in order to stabilize atmospheric CO<sub>2</sub> concentration in the range of 350–400 ppmv

depends on the climate sensitivity. A larger sensitivity leads to greater warming and a larger carbon flux from the terrestrial biosphere and oceans due to positive climate-carbon cycle feedbacks, which in turn increases the required sequestration. Results will be presented here for climate sensitivities ( $\Delta T_{2x}$ ) of 2 and 4 °C.

In addition to prescribing fossil fuel emissions, land use emissions must be prescribed and are assumed to reach zero by 2050. Emissions of other GHGs and of aerosols must also be prescribed, as these determine the total radiative forcing associated with a given CO<sub>2</sub> increase. A common set of assumptions is made here for Scenarios 1–4 and is given in Table I. Also given in Table I is a more stringent set of assumptions, which is combined with the CO<sub>2</sub> emission assumptions of Scenario 4 to create Scenario 5. For all scenarios, it is assumed that the fossil-fuel-related radiative forcing by ozone decreases by a factor of three relative to fossil fuel CO<sub>2</sub> emissions, and the ratio of sulphur to fossil fuel CO<sub>2</sub> emissions decreases by a factor of four. These are consistent with growing concerns over local and regional air pollution, and are well within the scope of technical feasibility (as briefly reviewed in Harvey (2004)). Radiative forcings and atmospheric lifespans of all non-CO<sub>2</sub> GHGs except CH<sub>4</sub> are taken from Ramaswamy et al. (2001). The buildup of atmospheric CH<sub>4</sub> is computed using the model of Osborn and Wigley (1994), which accounts for the feedback between CH<sub>4</sub> concentration and its atmospheric lifespan.

Figure 2 shows atmospheric CO<sub>2</sub> concentration for Scenarios 1–4. The difference between Scenarios 1 and 2 represents the impact of doubling the rate of decrease in energy intensity, the difference between Scenarios 2 and 3 largely represents the effect of quadrupling the rate of deployment of carbon-free energy, and the difference between Scenarios 3 and 4 represents the effect of lower population and per capita GDP growth (the relative sizes of these differences would be different if the driving factors were changed in a different order). The increase in atmospheric CO<sub>2</sub> concentration by 2200 is 35–65 ppmv greater for a 4 °C sensitivity than for a 2 °C sensitivity due to the stronger positive climate-carbon cycle feedback in the former case (the positive climate-carbon cycle feedback here is much weaker than found by Cox et al. (2000), implying that the increase in CO<sub>2</sub> concentration presented here for a given emission scenario could be too optimistic). For Scenarios 1–4, the atmospheric CO<sub>2</sub> concentration reaches about 1395–1460 ppmv, 660–700 ppmv, 480–520 ppmv, 425–460 ppmv, respectively, by 2200.

Figure 3 shows the change in global average temperature for Scenarios 1–5 for  $\Delta T_{2x} = 2$  and 4 °C. In Scenario 5, the CO<sub>2</sub> concentration peaks at 428 ppmv and 435 ppmv for  $\Delta T_{2x} = 2$  and 4 °C, respectively, and the equivalent peak CO<sub>2</sub> concentrations are 537 and 550 ppmv (compared to 560 ppmv for a doubling of the pre-industrial concentration). Thus, as noted earlier, a CO<sub>2</sub> concentration of 450 ppmv corresponds very closely to a doubling in the effective concentration in Scenario 5. However, this effective doubling is not sustained, so the peak warming is less than the equilibrium warming: 1.80 °C for  $\Delta T_{2x} = 2$  °C and 3.45 °C for  $\Delta T_{2x} = 4$  °C. Thus, although a CO<sub>2</sub> concentration of 450 ppmv clearly constitutes

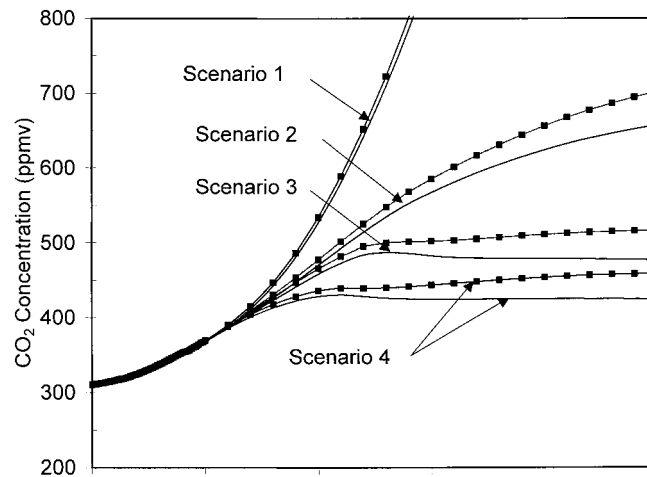


Figure 2. Atmospheric CO<sub>2</sub> concentration for scenarios one to four. For each scenario, the CO<sub>2</sub> concentration is given using a climate sensitivity of 2 °C (lower curve) and 4 °C (upper curve).

‘dangerous’ climate change (because  $\Delta T_{2x}$  could be as large as 4 °C), the danger is slightly reduced if the peak effective-CO<sub>2</sub> concentration is short-lived.

## 5. Potential Role of Carbon Sequestration

To understand the impact of carbon sequestration, it is useful to first examine the response of the oceanic part of the carbon cycle model to a pulse injection of CO<sub>2</sub> into the atmosphere and to a pulse injection of CO<sub>2</sub> into the ocean at various depths. This is referred to as the ‘impulse response’. As well, comparison with the impulse response computed by 3D ocean models serves to at-least partially validate the model used.

### 5.1. IMPULSE RESPONSE

Figure 4 shows the impulse response of the carbon cycle model to the sudden injection of 1 Gt C into (a) the atmosphere, (b) the deep ocean (at a depth of 3000 m), and (c) the shallow ocean (at a depth of 500 m). The impulse response is computed here without coupling to the climate model or the terrestrial biosphere part of the carbon cycle model. For the case of injection into the atmosphere, the fraction of carbon remaining in the atmosphere and the fraction taken up by the ocean are both shown. After 200 years, 70% of the injected carbon is taken up by the ocean, while after 2000 years (and in steady state), about 87% is taken up by the ocean and 13% remains in the atmosphere. When carbon is injected directly into the ocean, some of the carbon flows out of the ocean and into the atmosphere so that, in steady state, the atmosphere:ocean proportions are the same as when the CO<sub>2</sub> is injected directly

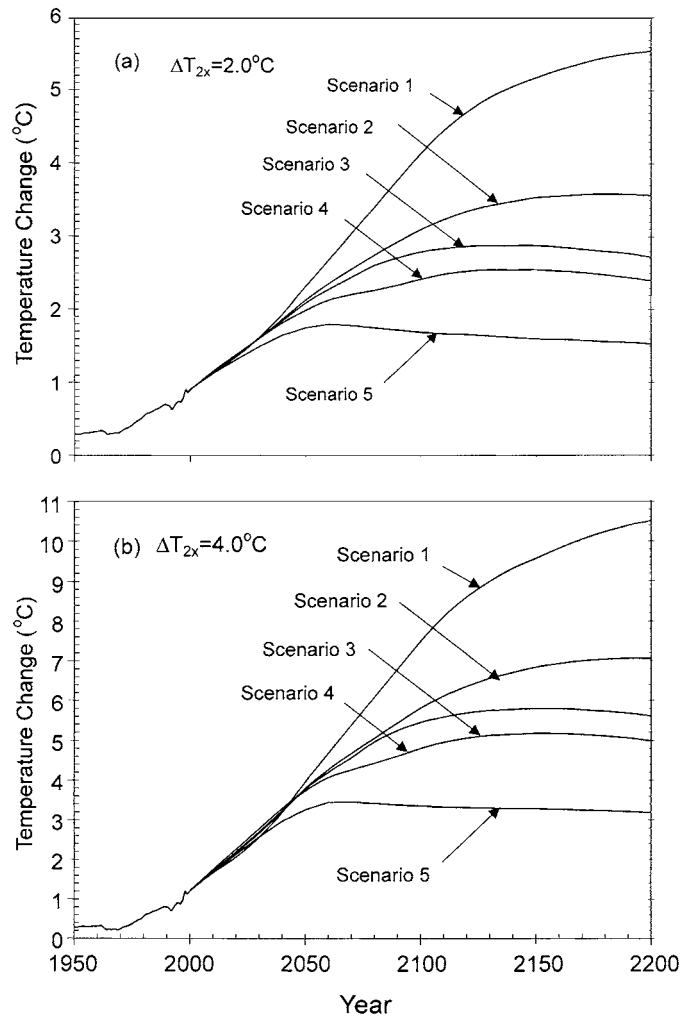


Figure 3. Global average temperature change (relative to 1765) for scenarios one to four assuming a climate sensitivity of (a) 2.0°C and (b) 4.0°C.

into the atmosphere, as one would expect. The model behavior for atmospheric injection is similar to that obtained by higher resolution models (Stocker et al., 1994). The model behavior shown in Figure 4 for both shallow and deep oceanic injection is similar to that obtained by Caldeira et al. (2001) for their runs using a one-dimensional box-diffusion ocean model for the case in which they allowed the atmospheric CO<sub>2</sub> content to respond to the efflux from the oceans (as in the simulations presented here). The results obtained with their box-diffusion ocean model in turn are similar to those obtained with a three-dimension ocean carbon cycle model. For this reason, Caldeira et al. (2001) conclude that a 1-D model is an appropriate tool for exploring basic conceptual issues associated with direct injection of CO<sub>2</sub>

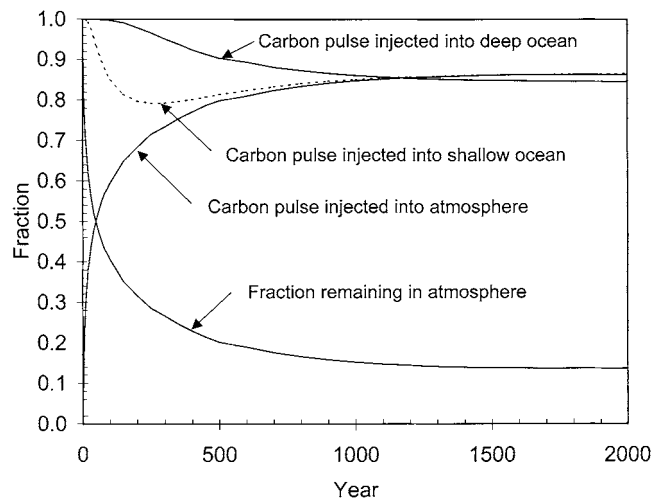


Figure 4. Fraction of carbon remaining in the ocean after injection of a pulse into the ocean, or accumulated in the ocean after emission of a pulse into the atmosphere. Also given is the fraction remaining in the atmosphere after emission of a pulse into the atmosphere.

into the ocean. The carbon cycle models used here and by Caldeira et al. (2001) do not allow for the partial dissolution contain  $\text{CaCO}_3$  sediments that would occur in reality, but this omission will only slightly alter the key simulation results to be presented in the next section. According to calculations by Kheshgi and Archer (1999), the effect of dissolution on atmospheric  $\text{CO}_2$  is negligible during the first 400 years, and would reduce the atmospheric  $\text{CO}_2$  fraction by about 4% after 2000 years. That is, the 13% of  $\text{CO}_2$  seen in the atmosphere in Figure 4 after 2000 years would be reduced to 9%.

## 5.2. TRANSIENT $\text{CO}_2$ CONCENTRATION

In this section, the impact of idealized carbon sequestration scenarios is considered, followed by the presentation of carbon sequestration scenarios that lead to compliance with the UNFCCC.

### 5.2.1. Idealized Carbon Sequestration Scenarios

Two carbon sequestration scenarios are considered here, one in which 1 Gt C per year is sequestered from 2020–2119 in geological reservoirs without leakage, and one in which the same amount of carbon is sequestered by injection into the ocean at a depth of 3000 m. The fully interactive climate-carbon cycle model with an interactive terrestrial biosphere is used. Sequestered carbon is subtracted from the fossil fuel emissions.

Figure 5a shows the change in the carbon content of the atmosphere, terrestrial biosphere, and oceans in response to geological burial of  $\text{CO}_2$  in Scenario 4. As soon as some  $\text{CO}_2$  is buried, the rate of increase in atmospheric  $\text{CO}_2$  slows down



and, as a result, the rate of absorption by the two natural carbon sinks decreases. After the first year, sequestration of 1 Gt C has reduced the atmospheric carbon content by only 0.93 Gt and caused a net decrease in the oceanic carbon content of 0.07 Gt C (the model uses one-year time steps, so a response of the terrestrial biosphere is not seen until year 2). By the end of 2119, after 100 Gt C have been sequestered, the atmospheric carbon content has decreased by 52 Gt C compared to the case without carbon sequestration, while the oceanic and terrestrial biosphere carbon contents have decreased by 27.7 Gt and 20.3 Gt, respectively. As soon as sequestration ceases, the reduction in atmospheric CO<sub>2</sub> content begins to be gradually (but only partially) reversed. This is because the sum of natural sinks plus artificial sequestration, which had exceeded anthropogenic emissions during the period of artificial sequestration, drops to less than anthropogenic emissions when artificial sequestration is terminated. Changes in the terrestrial biosphere track those in the atmosphere. The reduction in oceanic carbon content due to geological sequestration continues to grow, however, due to the continuing (albeit weakening) reduction in atmospheric CO<sub>2</sub> compared to the case without sequestration. By 3100, the reduction in atmospheric and oceanic carbon contents are about 24 Gt and 73 Gt, respectively, with negligible change in the carbon content of the terrestrial biosphere. Sequestration of 1 Gt C is the negative of an injection of 1 Gt C into the atmosphere, so the impact of sequestering 1 Gt C is similar to the negative of the impulse response shown in Figure 4 (except for transient effects from the terrestrial biosphere in the full model). Although the terrestrial biosphere has negligible longterm impact, it does reduce the peak impact of carbon sequestration and thus will noticeably affect the impact of carbon sequestration on the peak atmospheric CO<sub>2</sub> concentration for the baseline scenario considered here.

The weakening of the two natural sinks in response to geological sequestration is a form of leakage, in that it causes the net reduction in atmospheric CO<sub>2</sub> to be less than the cumulative carbon sequestration. In reality, real leakage of carbon from geological reservoirs could also occur, but is not considered here, as the goal here is to demonstrate the 'leakage' due to the dynamics of the carbon cycle without additional confounding factors. Furthermore, carbon sequestration would necessitate greater fossil fuel consumption, to supply the energy needed for sequestration, and this also would reduce the net reduction in atmospheric CO<sub>2</sub>. As noted in the introduction, an energy penalty as low as 2–5% might be achievable.

When 100 Gt C are directly injected into the ocean over a period of 100 years, the maximum increase in the oceanic carbon content is only 72 Gt (Figure 5b). This, however, is not due to the efflux of injected carbon back into the atmosphere, as the efflux begins to be important only much later (as seen in Figure 4). Rather, it is due to the feedback on the rate of absorption of atmospheric CO<sub>2</sub> due to the slower rate of buildup of atmospheric CO<sub>2</sub> once carbon sequestration begins. This is confirmed by the fact that the decrease in atmospheric carbon content at the end of 2119 with ocean sequestration (51.938 Gt) is almost exactly the same as with geological sequestration (51.995 Gt). However, by the end of the simulation, efflux

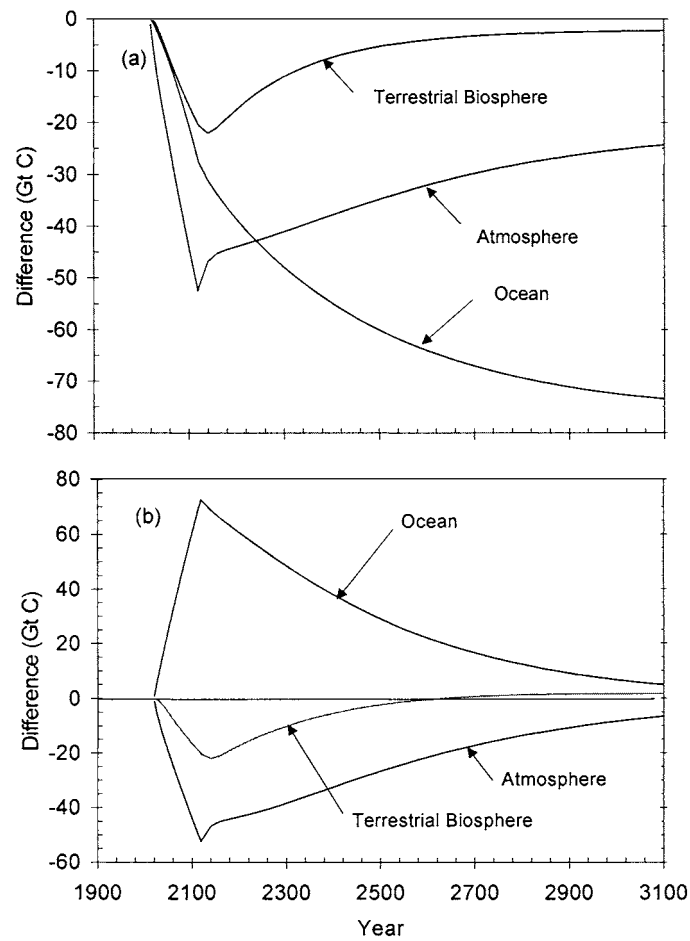


Figure 5. Change in the amount of carbon in the atmosphere, ocean, and terrestrial biosphere in response to an injection of 1 Gt C/year from 2020 to 2119 (100 Gt C total). CO<sub>2</sub> that would otherwise be emitted to the atmosphere is injected into (a) geological reservoirs and (b) the ocean at a depth of 3000 m.

of injected carbon from the ocean to the atmosphere is largely complete. Since this amounts to 15% of the injected carbon after 1000 years (Figure 4), the efflux from the ocean largely explains the difference in the reduction in atmospheric CO<sub>2</sub> in 3100 with geological sequestration (24% of the sequestered carbon, Figure 5a) and with deep ocean sequestration (7% of the sequestered carbon, Figure 5b). The small discrepancy arises from differences in the response of the terrestrial biosphere in the two cases.

The impact of carbon sequestration on atmospheric CO<sub>2</sub> can be represented by computing the effective carbon sequestration fraction. This is the decrease in atmospheric carbon content at any given time divided by the cumulative amount of carbon sequestered, and is analogous to the 'airborne fraction' concept used

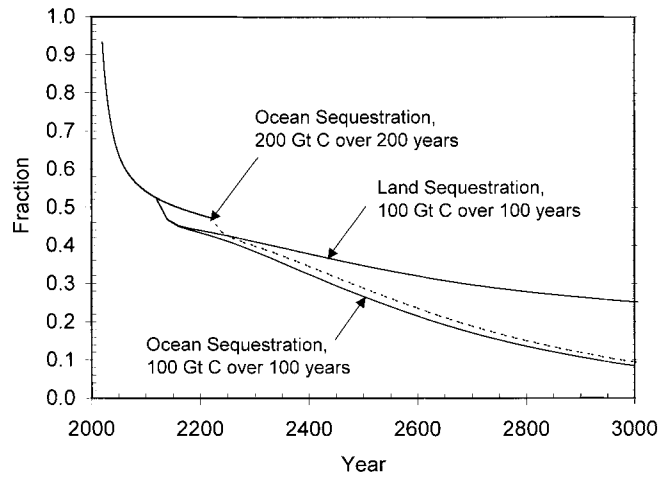


Figure 6. Variation in the cumulative sequestration fraction for sequestration into the deep ocean or in geological reservoirs of 1 Gt C/yr between 2020 and 2119 (100 Gt C), or of 1 Gt C/yr into the deep ocean between 2020 and 2219 (200 Gt C).

in analyzing emissions (see Harvey, 1989). The sequestration fraction is shown in Figure 6 for geological and oceanic sequestration. For the case of geological sequestration, the sequestration fraction is very similar to the airborne fraction shown in Figure 4 for a pulse injection into the atmosphere (indeed, the differences between Figures 4 and 6 are entirely due to the latter involving 100 'pulses' of sequestration of 1 Gt C each, rather than a single pulse). The sequestration fraction after one year is 0.93, and there is a continuous decrease in the sequestration fraction during the period of carbon sequestration. As soon as sequestration ceases, the rate of decrease in the sequestration fraction abruptly increases. This is related to the fact that new annual sequestration pulses, with their 0.93 effective retention, are no longer being averaged into the decreasing and smaller cumulative retention of all the preceding pulses. The model response to sequestration is linear for variations of a few 100 Gt in the total sequestration. As a result, the sequestration fraction curve is unchanged if the rate of sequestration is, for example, doubled to 2 Gt C/yr. This is similar to the behavior of the impulse response to an injection of CO<sub>2</sub> into the atmosphere as discussed, for example, by Harvey (1989). If sequestration of 1 Gt C/yr continues for 200 years rather than 100 years, the period of slow decrease in the sequestration fraction is prolonged, but the sequestration fraction quickly asymptotes to that obtained with 100 years of sequestration, as shown in Figure 6 for the case of ocean sequestration. There is a marked difference in the longterm geological and oceanic sequestration fractions, consistent with the difference seen between Figures 5a and 5b.

### 5.2.2. Targeted Carbon Sequestration Scenarios

We next consider the impact of idealized geological and oceanic carbon sequestration scenarios on absolute atmospheric CO<sub>2</sub> concentration, and determine sequestration scenarios that limit or return atmospheric CO<sub>2</sub> to concentrations in the 350–400 ppmv range.

Figure 7a compares the atmospheric CO<sub>2</sub> concentration for Scenario 4 and  $\Delta T_{2x} = 2^\circ\text{C}$  without carbon sequestration, with 1 Gt C/yr for 100 years in geological formations, in the oceans, and in both at the same time (the latter giving a total sequestration of 200 Gt C). Also shown, for comparison with the last case, are results in which 200 Gt C are sequestered in the oceans over a period of 100 years. For sequestration of 100 Gt C over 100 years in either geological reservoirs or the deep ocean, the peak atmospheric CO<sub>2</sub> concentration is reduced by about 10 ppmv (20 Gt C) and the maximal reduction is about 23 ppmv (46 Gt C). As soon as sequestration ceases, there is a temporary and identical rebound in atmospheric CO<sub>2</sub> concentration for the two cases. This is because the sum of natural sinks plus artificial sequestration no longer exceeds anthropogenic emissions. However, anthropogenic emissions are falling over time under Scenario 4, so the rebound in atmospheric CO<sub>2</sub> is small and short-lived. It is followed by a gradual decline in atmospheric CO<sub>2</sub>. Eflux from the ocean (for the case of oceanic sequestration) only begins to have a noticeable effect during this phase, long after the peak in atmospheric CO<sub>2</sub> concentration for Scenario 4, and so is not of great concern.

Figure 7b illustrates carbon sequestration scenarios which stabilize atmospheric CO<sub>2</sub> at approximately 350 ppmv for emission Scenario 4 with either a 2 or 4°C climate sensitivity. For  $\Delta T_{2x} = 2^\circ\text{C}$ , sequestration of 1 Gt C/yr in geological reservoirs for 200 years and 1 Gt C/yr in the oceans for 100 years is sufficient, whereas for  $\Delta T_{2x} = 4^\circ\text{C}$ , 2 Gt C/yr for 200 years need to be sequestered in geological reservoirs. The difference is due to the stronger positive climate-carbon cycle feedback when the climate sensitivity is larger.

Figure 7c shows sequestration scenarios that stabilize atmospheric CO<sub>2</sub> at 350–400 ppmv for emission Scenario 3, in which fossil fuel emissions are not eliminated until 2100. The higher the climate sensitivity, the lower the CO<sub>2</sub> concentration cap that one might want, but the harder one will have to work to comply with it, due to the higher the CO<sub>2</sub> concentration as a result of a stronger positive climate-carbon cycle feedback. For  $\Delta T_{2x} = 4^\circ\text{C}$ , atmospheric CO<sub>2</sub> peaks at 517 ppmv without sequestration. This is 167 ppmv or about 356 Gt C above 350 ppmv, and since the cumulative sequestration fraction is about 0.5 after 200 years (Figure 6), one can expect that about 700 Gt C would need to be sequestered. In fact, sequestration of 600 Gt C over 200 years draws atmospheric CO<sub>2</sub> down to 368 ppmv. This is followed by a gradual rebound which would be partly if not entirely eliminated if the effect of dissolution of carbonate sediments were accounted for.

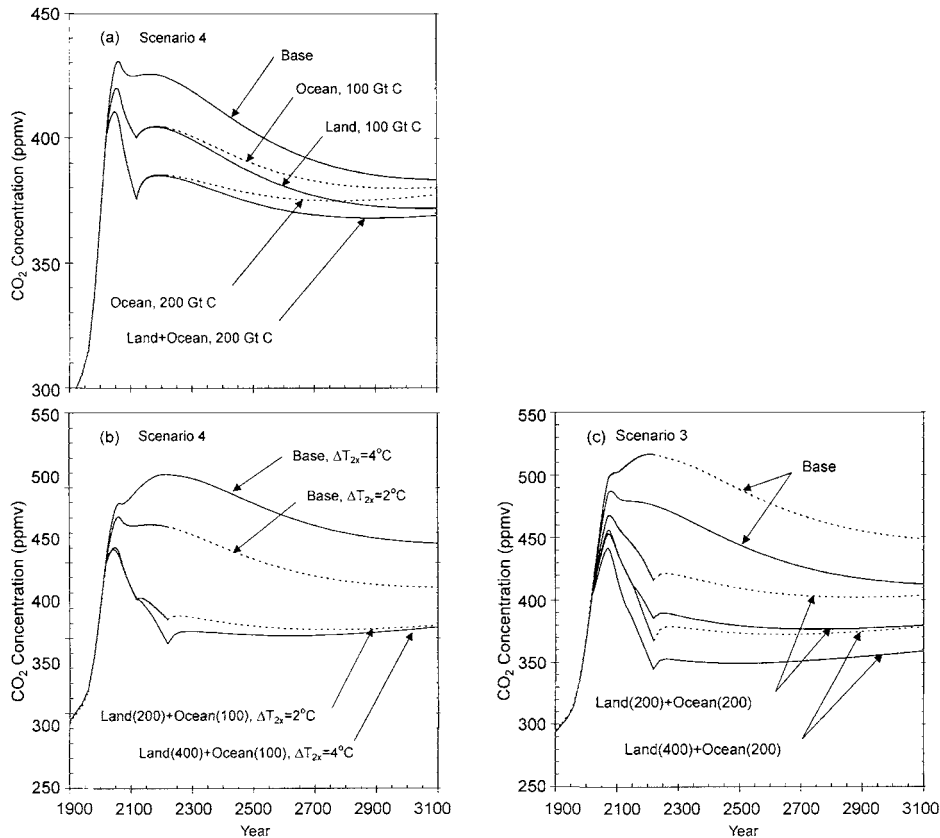


Figure 7. (a) Variation in atmospheric CO<sub>2</sub> concentration for emission Scenario 4 and  $\Delta T_{2x} = 2.0^\circ\text{C}$  with no carbon sequestration (base case) or with sequestration of 1 Gt C/yr between 2020–2119 into geological reservoirs, the deep ocean, or both geological reservoirs and the deep ocean. Also shown is the case when 2 Gt C/yr are sequestered into the deep ocean. (b) Same as (a), except for  $\Delta T_{2x} = 2.0^\circ\text{C}$  and for the base case or for sequestration of 1 Gt C/yr each into geological reservoirs and the deep ocean between 2020–2119, followed by 1 Gt C/yr into geological reservoirs between 2120–2219; or  $\Delta T_{2x} = 4.0^\circ\text{C}$  and the base case or sequestration of 2 Gt C/yr into geological reservoirs and 1 Gt C/yr into the deep ocean between 2020–2119, followed by 2 Gt C/yr into geological reservoirs between 2120–2219. (c) Same as (a), except for emission Scenario 3 and  $\Delta T_{2x} = 2.0^\circ\text{C}$  or  $4.0^\circ\text{C}$  for the case with no sequestration, for sequestration of 1 Gt C/yr yr each into geological reservoirs and the deep ocean between 2020–2219, and for sequestration of 2 Gt C/yr into geological reservoirs and 1 Gt C/yr into the deep ocean between 2020–2219.

### 5.3. IMPLIED MINIMUM RATE OF PROVISION OF BIOMASS ENERGY

In Scenarios 3 and 4, fossil fuel emissions decrease to zero by 2075 and 2100, respectively. Sequestration of carbon therefore requires provision of biomass energy with separation and capture of the released CO<sub>2</sub> in large enough quantity that the assumed carbon sequestration rates can be achieved. As noted in the introduction, this could be most easily achieved if biomass energy were gasified to produce

hydrogen, which would produce a stream of almost pure CO<sub>2</sub> as a byproduct. This CO<sub>2</sub> could be collected, compressed, and transported to sequestration sites at relatively little cost.

To assess the required minimum rate of provision of biomass energy, I have assumed that any required sequestration comes from fossil fuels up to the total fossil fuel emission (i.e., no CO<sub>2</sub> released from fossil fuels goes uncaptured unless the sequestration requirement has been met). Any deficit in the required sequestration comes from biomass energy. The required production of biomass energy is computed assuming a heating value for biomass of 18 GJ/tonne (from a range of 18–20 kg GJ/tonne for wood) and a carbon content of 70% by weight. For a sequestration rate of 3.5 Gt C/yr after all fossil fuel use has ended (the maximum considered here), 90 EJ/yr of biomass primary energy would need to be produced. Since not all biomass energy will be amenable for CO<sub>2</sub> capture, the required rate of provision of biomass energy would in fact be larger, perhaps by a large margin.

A number of analyses (Lazarus et al., 1993; WEC, 1994; Kassler, 1994; Ishitani et al., 1996) indicate that biomass could provide 100–300 EJ/yr on a sustainable basis, using what would otherwise be biomass waste and using land unsuited for agriculture. However, much of this biomass energy would be from dispersed sources and probably not amenable to the large-scale, centralized gasification and sequestration of carbon that would probably be necessary on economic grounds. Thus, even if the analyses of the potential for biomass energy are not overly optimistic, achieving the rates of sequestration of biomass carbon that might be deemed necessary (particularly if  $\Delta T_{2x} = 4^\circ\text{C}$ ) might not be possible. This underlines the importance of limiting fossil fuel emissions as rapidly as possible so as to minimize the magnitude of negative emissions that might need to be created in the near future in order to avoid unacceptable climatic change (or, at least, to minimize its duration).

It is possible that part of the sequestration requirement identified here could be met by increasing soil carbon. Metting et al. (2001), while acknowledging that the uncertainties are large and that there are significant gaps in our understanding of the structure and dynamics of soil carbon, indicate a worldwide technical potential to sequester 5.7–8.7 Gt C/yr in soils for up to 50 years. In practice, 1–2 Gt C/yr might be achievable if there were sufficient political will to do so. Of particular interest is the possibility, discussed by Metting et al. (2001), of sequestering 0.5–0.8 Gt C/yr in the soils of biomass cropland, while harvesting biomass crops for energy use. Schlesinger (2000) cautions that the net sink for CO<sub>2</sub> resulting from building up soil carbon can be zero after CO<sub>2</sub> emissions associated with the production of nitrogen fertilizer are accounted for, but these emissions could be eliminated if hydrogen is produced from renewable energy sources and used both as a chemical feedstock and as an energy input. Another option is the burial in the deep ocean as crop residues (Metzger and Benford, 2001), although this is not without some controversy (Metzger et al., 2002; Keith and Rhodes, 2002).

#### 5.4. TRANSIENT TEMPERATURE VARIATION

Figure 8 shows the variation in globally-averaged surface air temperature for Scenarios 3 and 4 without carbon sequestration, and for Scenario 4 with carbon sequestration sufficient to draw the atmospheric CO<sub>2</sub> concentration down to about 350 ppmv. Results are shown for  $\Delta T_{2x} = 2^\circ\text{C}$  and  $4^\circ\text{C}$ . Also given are results for Scenario 5 with the same carbon sequestration as in Scenario 4 so that the relative impact of carbon sequestration and stringent restrictions on non-CO<sub>2</sub> GHGs can be seen. For  $\Delta T_{2x} = 2^\circ\text{C}$ , the long term warming under Scenario 5 is about  $1^\circ\text{C}$ , although peak warming reaches  $1.7^\circ\text{C}$  because the GHG concentrations rise to the equivalent of a CO<sub>2</sub> doubling before the CO<sub>2</sub> concentration begins to decrease. For  $\Delta T_{2x} = 4^\circ\text{C}$ , the peak warming is  $3.2^\circ\text{C}$  and the longterm warming is  $1.8^\circ\text{C}$ .

An important conclusion is that it is not possible, even with rapid CO<sub>2</sub> emission reductions, maximal sequestration of biomass carbon, and sharp reductions in heating from methane and tropospheric ozone, to avoid a century or more of CO<sub>2</sub>-doubled climate. There are still benefits in reducing the CO<sub>2</sub> concentration as rapidly as possible during this transient warmth, however, as sea level rise due to thermal expansion would be reduced and it might be possible to avoid the irreversible melting of the Greenland ice sheet and destabilization of the West Antarctic ice sheet, processes that could take hundreds of years to be triggered. Abrupt re-organization of the oceanic circulation might also be averted if the peak warming is relatively short-lived. Finally, although massive deterioration of coral reef ecosystems worldwide is expected from as little as  $1\text{--}2^\circ\text{C}$  warming, outright extinction of coral organisms is not expected (Hoegh-Guldberg, 1999; Wilkinson, 1999). Recovery is possible, over a period ranging from hundreds to thousands of years. This will be more likely the shorter the period of high temperatures, if outright extinction can be avoided.

It is worth emphasizing that rapid reductions in fossil fuel emissions are required during this century (to essentially zero), combined with sequestration of at least  $1\text{--}2\text{ Gt C/yr}$  for much of the coming century (depending on the magnitude of positive climate-carbon cycle feedbacks) in order to have the *option* of peaking at no more than a doubled-CO<sub>2</sub> climate. If, by the time this climate is reached, the climate sensitivity is found to be small (something we will surely know by then) and the resulting temperature changes are deemed to be acceptable, then carbon sequestration need not continue. However, for reasons explained earlier, it is exceedingly unlikely that phasing out use of fossil fuels this century will have turned out to have been unnecessary.

#### 5.5. IMPACT ON SURFACE WATER CHEMISTRY

The oceanic part of the carbon cycle model used here contains the standard 7-component carbonate chemistry set of equations given in Peng et al. (1987), and so is suitable for assessing the global average effect of the uptake of CO<sub>2</sub> on the pH and concentration of dissolved carbonate ion (CO<sub>3</sub><sup>2-</sup>) in the surface layer of the

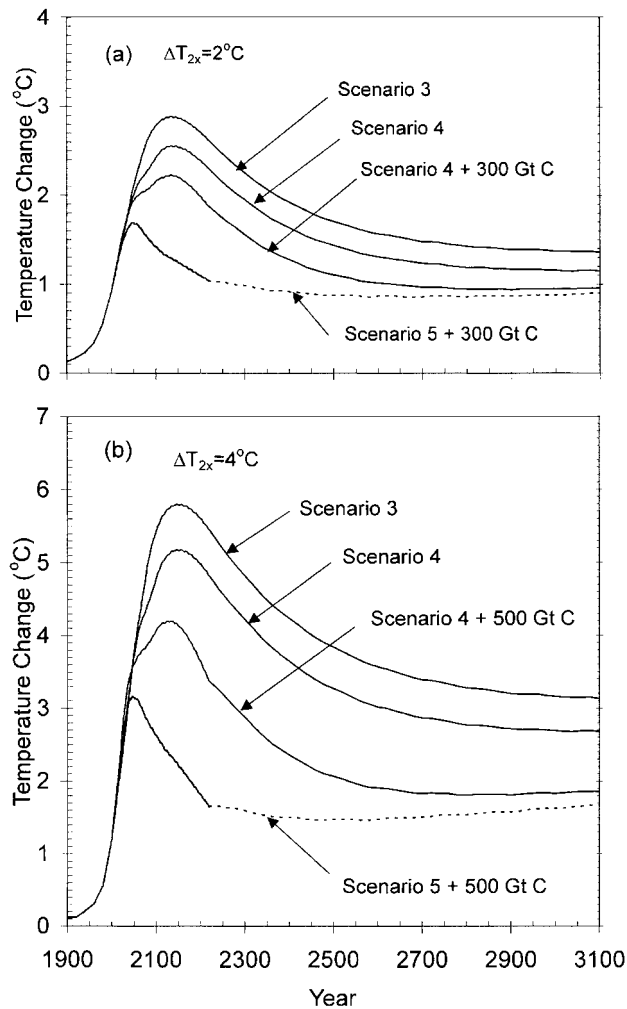


Figure 8. (a) Globally averaged temperature change for Scenario 4 for cases with no carbon sequestration ( $\Delta T_{2x} = 2.0^\circ\text{C}$  or  $4.0^\circ\text{C}$ ), for  $\Delta T_{2x} = 2.0^\circ\text{C}$  with a total sequestration of 300 Gt C, and for  $4.0^\circ\text{C}$  with a total sequestration of 450 Gt C, as in Figure 7b. (b) Globally averaged temperature change for scenario 3 for cases with no carbon sequestration ( $\Delta T_{2x} = 2.0^\circ\text{C}$  or  $4.0^\circ\text{C}$ ), for  $\Delta T_{2x} = 2.0^\circ\text{C}$  with a total sequestration of 400 Gt C and for  $4.0^\circ\text{C}$  with a total sequestration of 600 Gt C, as in Figure 7c.

ocean. The impact of carbon sequestration on land and in the oceans on the pH and the degree of supersaturation of the surface layer with respect to the calcite form of  $\text{CaCO}_3$  is shown in Figure 9 for Scenario 3 (without sequestration), and for cases in which 200 Gt C are sequestered in the oceans only with 0, 200, or 400 Gt C also sequestered in geological formations.

For the case without sequestration (which corresponds to a peak atmospheric  $\text{CO}_2$  concentration of about 480 ppmv), the supersaturation decreases from about



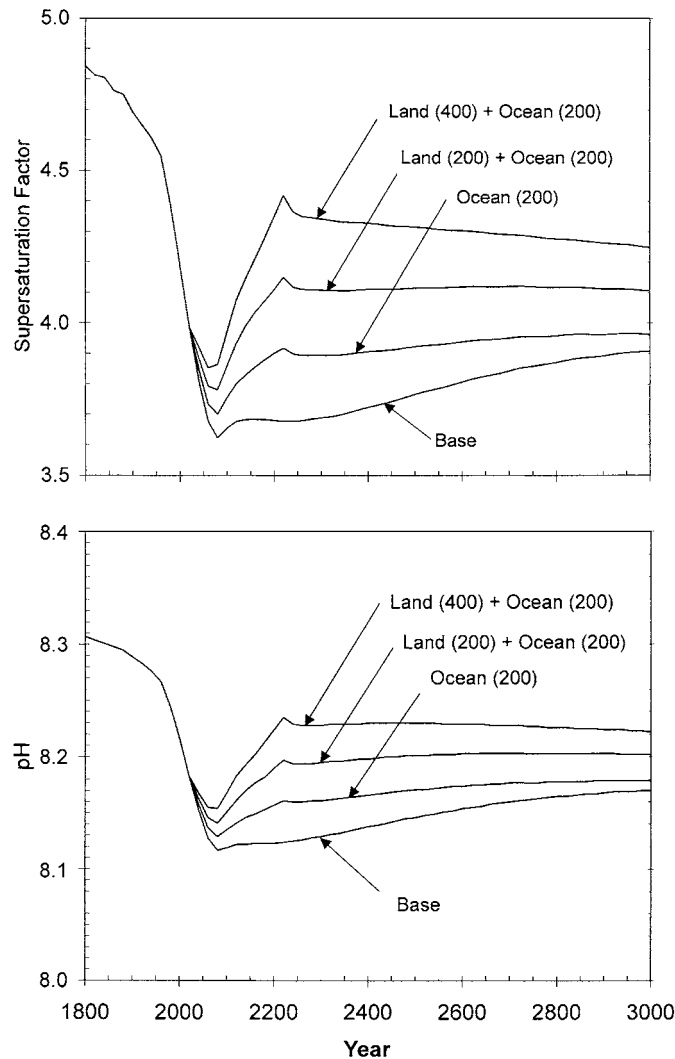


Figure 9. Variation in (a) supersaturation with respect to calcite, and (b) the pH of the non-polar mixed layer for Scenario 3 with and without various amounts of carbon sequestration.

480% in 1800 to 360% in 2080 – a decrease of 25%. The pH decreases from 8.31 to 8.12. It is possible that the impacts of changes of this magnitude could be modest, although uncertainties are large (Haugan and Drange, 1996; Wolf-Gladrow et al., 1999; Riebesell et al., 2000). There is nevertheless a risk of significant deleterious effects on marine productivity even if  $\text{CO}_2$  peaks near 450 ppmv. For Scenario 2 – considered by some to already represent a substantial constraint on fossil fuel emissions – the supersaturation decreases to 290% and the pH decreases by 0.32 units, while for Scenario 1 – a more typical business-as-usual scenario – the supersaturation decreases to 155% and the pH decreases by 0.6 units. The above-cited

papers indicate significant negative impacts for changes this large. This reiterates one of the central points of this paper, that a CO<sub>2</sub> increase significantly beyond 450 ppmv poses substantial risks, and hence, that 450 ppmv should be regarded as the *upper* limit of acceptable concentrations.

Sequestration of 200 Gt C in the deep ocean only slightly reduces the peak effect on the supersaturation and pH, but speeds the partial recovery that occurs after the peak. There is, however, little difference by 3100, since oceanic sequestration is simply speeding up the natural uptake and downward mixing of CO<sub>2</sub>. Sequestration of 200 Gt in the ocean and 400 Gt in geological reservoirs reduces the peak decrease in the supersaturation from 25% to 20% of the pre-industrial supersaturation. For emission Scenario 4 (not shown), supersaturation decreases by 20% for the case without any sequestration, and by 17% for sequestration of 300 Gt C.

It should be noted that the local effects on the marine biota, next to the deep-ocean CO<sub>2</sub> injection sites, are also of concern (Adams et al., 1997; Auerbach et al., 1997; Drange et al., 2001; Shirayama, 1997). Minimization of these effects requires injecting CO<sub>2</sub> from a large number of dispersed points rather than from a small number of large injection sites.

## 6. Concluding Comments

This paper has shown that the benefit (in terms of reduced atmospheric CO<sub>2</sub> content) of sequestering a given amount of carbon in geological reservoirs or in the deep ocean rapidly decreases over time, even if there is no leakage of the sequestered carbon. This is a consequence of a reduction in the absorption of atmospheric CO<sub>2</sub> by the natural carbon sinks (the terrestrial biosphere and oceans) in response to the slower buildup of atmospheric CO<sub>2</sub> that results from sequestration. Since sequestering a given amount of carbon is the same as not emitting the same amount, it follows that the impact of a given emission reduction will decrease over time in the same way. This, of course, is why emissions need to be continuously decreased after an initial reduction sufficient to stabilize the atmospheric CO<sub>2</sub> concentration, if one wishes to maintain a stable concentration (see Harvey, 1989). That is, the need for continuous emission reduction and a declining sequestration fraction are flip sides of the same coin.

A clear implication of the scenarios presented here is that there is no time to waste in beginning a rapid reduction in CO<sub>2</sub> emissions. It takes a combination of optimistic or extreme assumptions (low population growth, per capita economic growth declining from 1.6% per year in 2000 to 0.8% per year in 2100, high rates of improvement in energy efficiency and in the installation of carbon-free energy sources, and stringent reductions in non-CO<sub>2</sub> GHGs) combined with luck (the true climate sensitivity being 2 °C rather than 4 °C or more) in order to limit global average temperature change to 2 °C – a value that might already be sufficient to kill

most or all of the coral reefs in the world and which would provoke some damage to terrestrial ecosystems. The United Nations Framework Convention on Climate Change, a legally-binding document signed by all the major CO<sub>2</sub> emitters, declares its goal to be the stabilisation of GHG concentrations at levels that 'prevent dangerous anthropogenic interference with the climate system'. Dangerous is defined as meaning concentrations (and associated magnitudes and rates of climatic change) such that ecosystems cannot adjust to climatic change, or that lead to reduced global food production, or that imperil sustainable economic development (which requires continued provision of ecosystem services). The term 'dangerous' implies that undue *risk* is to be avoided. It is not necessary that it be proven that a CO<sub>2</sub> concentration of 450 ppmv, for example, will outstrip the ability of ecosystems to adapt, or reduce global food production; it is merely sufficient to show that there is a non-negligible risk of this happening. A CO<sub>2</sub> concentration of 450 ppmv corresponds to a doubling of the pre-industrial concentration if the heating effect of increases in other GHGs is added to that from CO<sub>2</sub>. There is a non-negligible probability that a CO<sub>2</sub>-doubling equivalent could provoke a globally-averaged temperature increase of 4–5°C, and the associated CO<sub>2</sub> concentration of 450 ppmv could have significant negative effects on the marine biota through changes in ocean chemistry, independently of the magnitude of the climatic response.

On this basis, a CO<sub>2</sub> concentration of 450 ppmv must, at present, be regarded as dangerous. Compliance with the UNFCCC therefore requires developing an international framework to stabilise the atmospheric CO<sub>2</sub> concentration at a value substantially less than 450 ppmv. However, peaking at or close to 450 ppmv seems to be unavoidable, so negative emissions will be needed to draw the CO<sub>2</sub> concentration down to lower values. If, by the time the CO<sub>2</sub> concentration peaks at a value near 450 ppmv, improved knowledge has shown that a concentration of 450 ppmv does not, in fact, imperil critical ecosystems and food production, then the additional effort needed to draw down the atmospheric concentration can be avoided. Until such time, prudence requires that we keep open the option of stabilising the atmospheric CO<sub>2</sub> concentration at a value below 450 ppmv.

In order to achieve a sufficiently rapid reduction in fossil fuel emissions that carbon sequestration of biomass CO<sub>2</sub> can be used to reduce the atmospheric CO<sub>2</sub> concentration to 350 ppmv (or even to 400 ppmv), all four terms in Equation (1) need to be addressed: not only the energy intensity and carbon intensity of the global economy, but also population growth and per capita economic growth. The latter two are generally ignored in discussions of emission abatement. Although a sustained period of robust economic growth is clearly needed in developing countries in order to provide a reasonable material standard of living, there may be a point in which greater per capita economic output is not associated with greater human welfare or happiness or, indeed, is correlated with declining wellbeing (see Daly and Cobb, 1989, Chapter 3). If ever-increasing GDP per capita is at some point traded for more day-to-leisure time, most people would probably regard this as leading to a higher quality of life, and it would certainly help to reduce the

growth of GHG emissions (particularly if energy-intensive leisure activities are discouraged through appropriate energy prices). To accept or even encourage lower economic growth requires a complete change in social values and political culture.

For an emission scenario in which fossil fuel emissions decrease to zero by the end of this century, carbon sequestration at a rate of 3.5 Gt C/yr is required for 100 years in order to return the atmospheric CO<sub>2</sub> concentration to 350 ppmv after peaking at 450 ppmv and persisting above 400 ppmv for 100 years. For the more aggressive scenario, in which fossil fuel emissions decrease to zero by 2075, sequestration of 2 Gt C/yr for 100 years would be sufficient to bring the concentration close to 350 ppmv.

However, it is not clear that the required carbon sequestration rates could be maintained after fossil fuel use has been completely phased out, given that CO<sub>2</sub> from significant quantities of biomass would need to be collected and transported to sequestration sites. If fossil fuel emissions are not decreased to zero until 2100, and it is deemed necessary to draw the atmospheric CO<sub>2</sub> concentration back to 350 ppmv during the following 100 years or so, then 100% of the carbon released from the use of 90 EJ/yr of biomass energy (3.5 Gt C/yr) would need to be sequestered. This may not be possible, although it will likely be possible to meet part of the sequestration requirement (100–200 Gt C cumulative storage) by building up soil carbon.

Elsewhere (Harvey, 2003), the impact on long-term CO<sub>2</sub> concentrations and on ocean chemistry of unrestrained CO<sub>2</sub> emissions or of much larger oceanic carbon sequestration than considered here is presented. Large-scale reliance on oceanic sequestration is clearly unacceptable from an environmental point of view. However, the amount of carbon that needs to be sequestered in order to draw atmospheric CO<sub>2</sub> back to 350 ppmv might, even under aggressive emission-reduction scenarios, largely use up the safe carbon storage capacity in geological formations (as little as 300 Gt C) and in the oceans (100–200 Gt C, given that the oceans will eventually absorb most of the CO<sub>2</sub> already emitted). Thus, however optimistic one might be concerning the prospects for carbon sequestration, significant and rapid near-term reductions in the use of fossil fuels are required.

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## References

- Adams, E. E., Caulfield, A. J., Herzog, H. J., and Auerbach, D. I.: 1997, 'Impacts of Reduced pH from Ocean CO<sub>2</sub> Disposal: Sensitivity of Zooplankton Mortality to Model Parameters', *Waste Management* **17**, 375–380.
- Aggarwal, P. K. and Mall, R. K.: 2002, 'Climate Change and Rice Yields in Diverse Agro-Environments of India. II. Effect of Uncertainties in Scenarios and Crop Models on Impact Assessment', *Clim. Change* **52**, 331–343.
- Andronova, N. G. and Schlesinger, M. E.: 2001, 'Objective Estimation of the Probability Density Function for Climate Sensitivity', *J. Geophys. Res.* **106**, 22605–22611.
- Arnell, N. W., Cannell, M. G. R., Hulme, M., Kovats, R. S., Mitchell, J. F. B., Nicholls, R. J., Parry, M. L., Livermore, M. T. J., and White, A.: 2002, 'The Consequences of CO<sub>2</sub> Stabilization for the Impacts of Climate Change', *Clim. Change* **53**, 413–446.
- Auerbach, D. I., Caulfield, J. A., Adams, E. E., and Herzog, H. J.: 1997, 'Impacts of Ocean CO<sub>2</sub> Disposal on Marine Life: 1. A Toxicological Assessment Integrating Constant-Concentration Laboratory Assay Data with Variable-Concentration Field Exposure', *Environ. Model. Assess.* **2**, 333–343.
- Azar, C. and Rodhe, H.: 1997, 'Targets for Stabilization of Atmospheric CO<sub>2</sub>', *Science* **276**, 1818–1819.
- Byrer, C. W. and Guthrie, H. D.: 1999, 'Coal Deposits: Potential Geological Sink for Sequestering Carbon Dioxide Emissions from Power Plants', in Riemer, P., Eliasson, B., and Wokaun, A. (eds.), *Greenhouse Gas Control Technologies*, Elsevier Science, New York, pp. 181–187.
- Caldeira, K., Herzog, H. J., and Wickett, M. E.: 2001, 'Predicting and Evaluating the Effectiveness of Ocean Carbon Sequestration by Direct Injection', presented at the *First National Conference on Carbon Sequestration*, Washington, D.C., 14–17 May 2001.
- Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: 2000, 'Acceleration of Global Warming Due to Carbon-Cycle Feedbacks in a Coupled Climate Model', *Nature* **408**, 184–187.
- Daly, H. E.: 1996, *Beyond Growth*, Beacon Press, Boston, 253 pp.
- Daly, H. E. and Cobb, J. B.: 1989, *For the Common Good: Redirecting the Economy Toward Community, the Environment, and a Sustainable Future*, Beacon Press, Boston, 482 pp.
- Darwin, R. and Kennedy, D.: 2000, 'Economic Effects of CO<sub>2</sub> Fertilization of Crops: Transforming Changes in Yield into Changes in Supply', *Environ. Model. Assess.* **5**, 157–168.
- David, J. and Herzog, H.: 2000, 'The Cost of Carbon Capture', in *Fifth International Conference on Greenhouse Gas Control Technologies*, Cairns, Australia, 13–16 August 2000.
- Dennis, C.: 2002, 'Reef under Threat from "Bleaching" outbreak', *Nature* **415**, 947.
- Drange, H., Alendal, G., and Johannessen, O. M.: 2001, 'Ocean Release of Fossil Fuel CO<sub>2</sub>: A Case Study', *Geophys. Res. Lett.* **28**, 2637–2640.
- Edmonds, J. and Reilly, J.: 1983, 'A Long-Term Global Energy-Economic Model of Carbon Dioxide Release from Fossil Fuel Use', *Energy Economics* **5**, 74–88.
- Forest, C. E., Stone, P. H., Sokolov, A. P., Allen, M. R., and Webster, M. D.: 2002, 'Quantifying Uncertainties in Climate System Properties with the Use of Recent Climate Observations', *Science* **295**, 113–117.
- Gitay, H. et al.: 2001, 'Ecosystems and their Goods and Services', in McCarthy, J. J., Canziani, O. S., Leary, N. A., Dokken, D. J., and White, K. S. (eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Cambridge University Press, Cambridge, pp. 235–342.
- Harvey, L. D. D.: 1989, 'Managing Atmospheric CO<sub>2</sub>', *Clim. Change* **15**, 343–381.
- Harvey, L. D. D.: 2000, *Global Warming: The Hard Science*, Prentice Hall, Harlow, U.K., 336 pp.
- Harvey, L. D. D.: 2002, 'A Quasi-One-Dimensional Coupled Climate-Carbon Cycle Model. Part II: The Carbon Cycle Component', *J. Geophys. Res. – Oceans* **106**, 22355–22372, 2001.
- Harvey, L. D. D.: 2003, 'Impact of Deep-Ocean Carbon Sequestration on Atmospheric CO<sub>2</sub> and on Surface-Water Chemistry', *Geophys. Res. Lett.* **30** (5), doi:10.1029/2002GL016224.

- Harvey, L. D. D.: 2004, 'Climatic Change Drivers', in Lovejoy, T. and Hannah, L. (eds.), *Climate Change and Biodiversity*, Yale University Press, accepted.
- Harvey, L. D. D.: 2005, *Energy and the New Reality: Facing up to Climatic Change*, Island Press, Washington, in preparation.
- Harvey, L. D. D. and Huang, Z.: 2001, 'A Quasi-One-Dimensional Coupled Climate-Carbon Cycle Model, Part 1: Description and Behavior of the Climate Component', *J. Geophys. Res. – Oceans* **106**, 22339–22353.
- Harvey, L. D. D. and Kaufmann, R. K.: 2002, 'Simultaneously Constraining Climate Sensitivity and Aerosol Radiative Forcing', *J. Climate* **15**, 2837–2861.
- Haugan, P. M. and Drange, H.: 1996, 'Effects of CO<sub>2</sub> on the Ocean Environment', *Energy Convers. Mgmt* **37**, 1019–1022.
- Haugen, H. S. and Eide, L. I.: 1996, 'CO<sub>2</sub> Capture and disposal: The Realism of Large-Scale Scenarios', *Energy Convers. Mgmt* **37**, 1061–1066.
- Herzog, H. J.: 2001, 'What Future for Carbon Capture and Sequestration?', *Environmental Science and Technology* **35**, 148–153.
- Hoegh-Guldberg, O.: 1999, 'Climate Change, Coral Bleaching and the Future of the World's Coral Reefs', *Mar. Freshwater Res.* **50**, 839–866.
- Hoffert, M. I. et al.: 1998, 'Energy Implications of Future Stabilization of Atmospheric CO<sub>2</sub> Content', *Nature* **395**, 881–884.
- Holloway, S.: 2001, 'Storage of Fossil Fuel-Derived Carbon Dioxide beneath the Surface of the Earth', *Annu. Rev. Energy Environ.* **26**, 145–166.
- Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. (eds.): 2001, *Climate Change 2001: The Scientific Basis*, Appendix II, SRES Tables, Cambridge University Press, Cambridge, pp. 799–826.
- International Energy Agency (IEA): 2001a, *Carbon Dioxide Capture from Power Stations*, OECD, Paris (available at: [www.ieagreen.org.uk](http://www.ieagreen.org.uk))
- International Energy Agency (IEA): 2001b, *Carbon Dioxide Disposal from Power Stations*, OECD, Paris (available at: [www.ieagreen.org.uk](http://www.ieagreen.org.uk))
- International Energy Agency (IEA): 2001c, *Ocean Storage of CO<sub>2</sub>*, OECD, Paris (available at: [www.ieagreen.org.uk](http://www.ieagreen.org.uk))
- Ishitani, H. et al.: 1996, 'Energy Supply Mitigation Options', in Watson, R. T., Zinyowera, M. C., and Moss, R. H. (eds.), *Climate Change 1995 – Impacts, Adaptation and Mitigation of Climate Change: Scientific Analysis*, Cambridge University Press, pp. 585–647.
- Keith, D. W. and Rhodes, J. S.: 2002, 'Bury, Burn or Both: A Two-for-One Deal on Biomass Carbon and Energy', *Clim. Change* **54**, 375–377.
- Kheshgi, H. S. and Archer, D. E.: 1999, 'Modelling the Evasion of CO<sub>2</sub> Injected into the Deep Ocean', in Riemer, P., Eliasson, B., and Wokaun, A. (eds.), *Greenhouse Gas Control Technologies*, Elsevier Science, New York, pp. 287–292.
- Kleypas, J.: 1998, 'Symposium Participants Assess Future of Coral Reefs', *EOS* **79** (21), 249, 251, 253.
- Kleypas, J.: 1999, 'Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs', *Science* **284**, 118–120.
- Knutti, R., Stocker, T. F., Joos, F., and Plattner, G.-K.: 2002, 'Constraints on Radiative Forcing and Future Climate Change from Observations and Climate Model Ensembles', *Nature* **416**, 719–723.
- Langdon, C., Takahashi, T., Sweeney, C., Chipman, D., Goddard, J., Marubini, F., Aceves, H., Barnett, H., and Atkinson, M.: 2000, 'Effect of Calcium Carbonate Saturation State on the Calcification Rate of an Experimental Coral Reef', *Global Biogeochem. Cycles* **14**, 639–654.
- Lazarus, M. L., Greber, L., Jall, J., Bartels, C., Bernow, S., Hansen, E., Raskin, P., and von Hippel, D.: 1993, *Towards a Fossil Fuel Free Energy Future: The Next Energy Transition*, Technical Analysis for Greenpeace International, Stockholm Environmental Institute Boston Center.

- Lutz, W., Sanderson, W., and Scherbov, S.: 2001, 'The End of World Population Growth', *Nature* **412**, 543–545.
- Marland, G., Boden, T. A., and Andres, R. J.: 2002, 'Global, Regional, and National Fossil Fuel CO<sub>2</sub> Emissions', in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A.
- Metting, F. B., Smith, J. L., Amthor, J. S., and Isaurralde, R. C.: 2001, 'Science Needs and New Technology for Increasing Soil Carbon Sequestration', *Clim. Change* **51**, 11–34.
- Metzger, R. A. and Benford, G.: 2002, 'Sequestration of Atmospheric Carbon through Permanent Disposal of Crop Residue', *Clim. Change* **49**, 11–19.
- Metzger, R. A., Benford, G., and Hoffert, M. I.: 2001, 'To Bury or Burn: Optimum Use of Crop Residues to Reduce Atmospheric CO<sub>2</sub>', *Clim. Change* **54**, 369–374.
- Morgan, M. G., Pitelka, L. F., and Shevliakova, E.: 2001, 'Elicitation of Expert Judgments of Climate Change Impacts on Forest Ecosystems', *Clim. Change* **49**, 279–307.
- Nihous, G. C.: 1997, 'Technological Challenges Associated with the Sequestration of CO<sub>2</sub> in the Ocean', *Waste Management* **17**, 337–341.
- Osborn, T. J. and Wigley, T. M. L.: 1994, 'A Simple Model for Estimating Methane Concentration and Lifetime Variations', *Clim. Dyn.* **9**: 181–193.
- Parry, M., Arnell, N., McMichael, T., Nicholls, R., Martens, P., Kovats, S., Livermore, M., Rosenzweig, C., Iglesias, A., and Fischer, G.: 2001, 'Millions at Risk: Defining Critical Climate Change Threats and Targets', *Global Environ Change* **11**, 181–183.
- Parson, E. A. and Keith, D. W.: 1998, 'Fossil Fuels without CO<sub>2</sub> Emissions', *Science* **282**, 1053–1054.
- Peng, T.-H., Takahashi, T., Broecker, W. S., and Olafsson, J.: 1987, 'Seasonal Variability of Carbon Dioxide, Nutrients and Oxygen in the Northern North Atlantic Surface Water: Observations and a Model', *Tellus* **39B**, 439–458.
- Prentice, I. C. et al.: 2001, 'The Carbon Cycle and Atmospheric Carbon Dioxide', in Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. (eds.), *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, pp. 183–237.
- Ramaswamy, V. et al.: 2001, 'Radiative Forcing of Climate Change', in Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A. (eds.), *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge, pp. 349–416.
- Riebesell, U., Zondervan, I., Rost, B., Tortell, P. D., Zeebe, R., and Morel, F. M. M.: 2000, 'Reduced Calcification of Marine Plankton in Response to Increased Atmospheric CO<sub>2</sub>', *Nature* **407**, 364–367.
- Riener, P., Eliasson, B., and Wokaun, A. (eds.): 1999, *Greenhouse Gas Control Technologies*, Elsevier Science, New York.
- Rosenzweig, C., Parry, M. L., Fischer, G., and Frohberg, K.: 1993, *Climate Change and World Food Supply*, Environmental Change Unit, University of Oxford, Research Report No. 3, 28 pp.
- Schlesinger, W. H.: 2000, 'Carbon Sequestration in Soils: Some Cautions Amidst Optimism', *Agric. Ecosystems Env.* **82**, 121–127.
- Shirayama, Y.: 1997, 'Biodiversity and Biological Impact of Ocean Disposal of Carbon Dioxide', *Waste Management* **17**, 381–384.
- Stocker, T. F., Broecker, W. S., and Wright, D. G.: 1994, 'Carbon Uptake Experiments with a Zonally-Averaged Global Ocean Circulation Model', *Tellus*, **46B**, 103–122.
- United Nations: 1992, *United Nations Framework Convention on Climate Change*, U.N. Doc. A/AC.237/18 (Part II)/Add.1, 15 May 1992.
- Wellington, G. M., Glynn, P. W., Strong, A. E., Navarrete, A., Wieters, E., and Hubbard, D.: 2001, 'Crisis on Coral Reefs Linked to Climate Change', *EOS* **82**(1), 1, 5.

- White, A., Melvin, G. R. C., and Friend, A. D., 1999: 'Climate Change Impacts on Ecosystem and the Terrestrial Carbon Sink: A New Assessment', *Global Environ Change* **9**, S21–S30.
- Wilkinson, C. R.: 1999, 'Global and Local Threats to Coral Reef Functioning and Existence: Review and Predictions', *Mar. Freshwater Res.* **50**, 867–878.
- Williams, R. H.: 1998, 'Fuel Decarbonization for Fuel Cell Applications and Sequestration of the Separated CO<sub>2</sub>', in Ayres, R. U. and Weaver, P. M. (eds.), *Ecorestructuring: Implications for Sustainable Development*, United Nations University Press, Tokyo, pp. 180–222.
- Wolfe, D. W. and Erickson, J. D.: 1993, 'Carbon Dioxide Effects on Plants: Uncertainties and Implications for Modeling Crop Response to Climate Change', in Kaiser, R. U. and Drennen, T. E. (eds.), *Agricultural Dimensions of Global Climate Change*, St. Lucie Press, Delray Beach Florida, pp. 153–178.
- Wolf-Gladrow, D. A., Riebesell, U., Buckhardt, S., and Bijma, J.: 1999, 'Direct Effects of CO<sub>2</sub> Concentration on Growth and Isotopic Composition of Marine Plankton', *Tellus* **51B**, 461–476.
- Worldwatch Institute, 2002: *Vital Signs 2002: The Trends that Are Shaping Our Future*, W. W. Norton, New York, 215 pp.

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